

Integration of Cryptocurrencies into Investment Portfolios: Application of Modern Portfolio Theory and Minimum Spanning Tree Analysis

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Abstract

The integration of cryptocurrencies into investment portfolios has been analysed through two main approaches: Modern Portfolio Theory (MPT) and Minimum Spanning Tree (MST) analysis. While previous research has demonstrated the potential to improve portfolio performance through cryptocurrency inclusion, the current study reveals a more nuanced picture. Empirical results indicate that, under Markowitz's theory, cryptocurrencies are assigned zero weights in the optimal portfolio, primarily due to their extreme volatility (exceeding 50–60% for assets such as DOGE-USD and MATIC-USD). Correlation analysis reveals strong relationships between major cryptocurrencies, such as BTC-USD and ETH-USD (above 0.85), while assets such as DOGE-USD and TRX-USD exhibit weaker correlations with other components (below 0.4). Despite their diversification potential, the high volatility of cryptocurrencies diminishes this effect. The optimal portfolio achieves results similar to

traditional benchmarks, with a return of 6.8% and risk around 12%. The study concludes that integrating cryptocurrencies into investment portfolios necessitates more dynamic risk management approaches.

Keywords: Cryptocurrency, Modern Portfolio Theory, Minimum Spanning Tree, Portfolio, Optimization.

JEL: C52; C58; G15; G17

Introduction

The topic of cryptocurrency portfolios within the frameworks of Modern Portfolio Theory (MPT) and Minimum Spanning Tree (MST) approaches has attracted considerable interest in recent years. The diverse literature in this field encompasses empirical studies, theoretical models, and practical applications, illustrating the dynamic interface between finance and technology. The research analyses how cryptocurrencies, traditionally perceived as high-risk assets, can be effectively integrated into diversified portfolios to optimize returns and manage risk.

Literature that examines the incorporation of cryptocurrencies into portfolios has gained

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much attention but with several critical areas left unexplored. Some of these are the long-term sustainability of the utilization of the asset class for portfolio diversification, the asset class' dynamic portfolio management, and the effect of macroeconomic conditions and market turbulence (Jana & Sahu, 2024; Eldomiaty & Khaled, 2024). Additional analysis of the asset class' performance under varying market conditions such as financial crisis times and times of increased market turbulence is necessary for it to be thoroughly comprehended for it to be utilized effectively as a vehicle for hedging (Xie et al., 2021).

The study seeks to construct a new analytical model that includes the use of cryptocurrencies within classical models of portfolio optimization. The study comes at the appropriate time due to the growing volatility of the markets for cryptocurrencies and the ability of these markets to impact investments substantially. With the use of cryptocurrencies within portfolio models of optimization, the investor should be able to benefit from the possibilities of diversification and enhanced risk management.

The contributions of the present study shall complement the portfolio optimization and crypto investments' literature by presenting valuable knowledge for scholars and practitioners alike. The combination of Modern Portfolio Theory (MPT) and Minimum Spanning Tree (MST) analysis creates a new insight for the examination of the resilience and efficiency of varying assets under varying market conditions. The combination of the risk-reward model of MPT with the network analysis of MST creates a more holistic outlook of asset performance.

By employing MST for a portfolio of assets, the most critical relationships between the assets are revealed and the degree of their

linkages measured. The gained knowledge can be leveraged for optimizing decisions for the portfolio and for increasing resilience under market conditions of uncertainty.

Many publications focus on applying MPT principles to cryptocurrency investments. Increasingly, studies examine the unique characteristics of cryptocurrencies, including their volatility and correlation dynamics with traditional asset classes. These studies highlight the challenges and opportunities of constructing cryptocurrency portfolios aligned with MPT requirements. Furthermore, the introduction of the Minimum Spanning Tree approach offers a new perspective on portfolio optimization, providing deeper insights into asset interrelationships and diversification strategies.

The growing interest in this area is evident from the substantial increase in the number of publications in recent years. The rise in academic articles, reports, and conference proceedings demonstrates the heightened interest among researchers in the complexities of cryptocurrency markets. Frequent citations of key studies underscore their impact and sustain the active dialogue among scholars in finance and investment.

Moreover, discussions on these topics continue to expand in response to real-world events in the cryptocurrency space, such as market fluctuations and regulatory changes. This dynamic environment likely fuels academic interest, leading to a continuous influx of new literature aimed at addressing current trends and challenges associated with digital currencies.

The remainder of the paper proceeds with the study organization as follows: Section 2 includes the critical examination of recent empirical research of the inclusion of cryptocurrencies into portfolios with the

most critical results and the most prominent methodological techniques highlighted. Section 3 includes the study framework and empirical techniques employed within the study, including the processes of collecting the data, the compilation of the network of correlations, and the execution of MPT and MST analysis.

Section 4 shows the primary findings of the study, with an emphasis on the effect of cryptocurrency inclusion on portfolio optimization, the risk-return trade-off, and diversification potential. In particular, Section 4.1 examines daily log returns, and Section 4.2 looks at the correlation matrix, plots the MST, and explores asset centrality. Section 4.3 compares optimized portfolios based on Markowitz's model, and Section 4.4 performs a comparative analysis with conventional benchmark portfolios.

The main results are presented in the final section, with discussion of the implications for practice and areas for future study suggested. Close attention here is paid to the continually evolving nature of crypto markets and the position of crypto markets within new financial models.

2. The Role of Cryptocurrencies in Investment Portfolio Optimization

Over the past decade, cryptocurrencies have emerged as a new asset class, attracting the attention of both individual and institutional investors. Cryptocurrencies are digital currencies based on cryptographic technologies, with their value determined by market demand, technological advancements, and investor sentiment (Li & Wang, 2017). The unique characteristics of these assets, including high volatility and relatively low correlation with traditional financial

instruments, present both challenges and opportunities for portfolio optimization.

Despite scepticism surrounding cryptocurrencies as financial assets (Jacobs, 2018), the complex nature of the cryptocurrency market—comprising thousands of digital currencies—offers potentially valuable mechanisms for predicting future market behaviour (Hong & Yoon, 2022). This highlights the importance of studying the integration of cryptocurrencies into investment portfolios through Modern Portfolio Theory (MPT) and other analytical methods, such as Minimum Spanning Tree (MST).

Modern Portfolio Theory, developed by Harry Markowitz, provides a fundamental framework for constructing optimal investment portfolios. The theory postulates that investors can build portfolios that maximize expected returns for a given level of risk or minimize risk for a desired level of return through a scientifically grounded asset allocation (Markowitz, 1952).

In the context of cryptocurrency investments, recent research demonstrates the applicability of MPT for optimizing portfolios that include digital assets. According to Andrianto (2017), the optimal allocation of cryptocurrencies in an investment portfolio ranges between 5% and 20%, depending on the investor's risk tolerance (Andrianto, 2017). Brauneis and Mestel (2019) found that portfolios constructed based on MPT principles achieve higher Sharpe ratios compared to investments in single cryptocurrencies (Brauneis & Mestel, 2019). Their study focuses on Bitcoin as a typical cryptocurrency and employs an equally weighted classification of crypto assets within the mean-variance Markowitz model to extract risk-adjusted returns. Research has also examined constructing portfolios

using MPT and the Sharpe ratio, combining stocks, commodities, and cryptocurrencies to create various optimal investment portfolios (Wang, 2023). MPT proves applicable to cryptocurrencies by providing valuable tools for optimizing portfolios that include digital assets (Chen, 2023). Additionally, a new approach based on Minimum Spanning Tree theory has been proposed for building portfolios that offer attractive results in terms of value growth and risk reduction for individual investors (Danko et al., 2020). Applying Markowitz's portfolio theory reveals that the expected risks of a cryptocurrency-inclusive portfolio are lower, and returns are higher compared to portfolios without cryptocurrencies (Ćosić & Časni, 2019). At the same time, studies indicate that from an MPT perspective, cryptocurrencies like Bitcoin lie on the efficient frontier, implying that investments in such instruments depend on the investor's risk appetite (Saksonova & Kuzmina-Merlino, 2019). These collective findings demonstrate the relevance and adaptability of MPT in the evolving landscape of digital finance.

A significant body of empirical research supports the potential benefits of including cryptocurrencies in investment portfolios. Studies suggest that incorporating cryptocurrencies such as Bitcoin into a portfolio of emerging market indices can improve portfolio performance. Ma et al. (2020) found that adding Bitcoin to traditional portfolios significantly enhances diversification effects, primarily due to the cryptocurrency's unique return and volatility profile (Ma et al., 2020). Katsiampa et al. (2022) extend these findings by including Ethereum in their analysis, demonstrating how a combination of various cryptocurrencies can contribute to more effective portfolio risk management

(Katsiampa et al., 2022). Bruhn and Ernst (2022) support this thesis by examining the risk characteristics of the cryptocurrency market, concluding that a portfolio including the largest cryptocurrencies by market capitalization can significantly improve the risk-return ratio (Bruhn & Ernst, 2022).

Studies recommend that portfolio managers construct global minimum variance portfolios to account for the substantial volatility of cryptocurrency markets. In the absence of complex optimization models, individual investors can allocate funds to cryptocurrencies based on their market value (Andrianto, 2017). Jana & Sahu (2023a) discover that the Indian market for stocks can be diversified using the use of cryptocurrencies, particularly under financial crisis conditions (Jana & Sahu, 2023a). The above expectation can be rationalized by the fact that they are of low correlation with traditional assets, according to previous empirical research (Brière et al., 2015; Zhang & Gregoriou, 2020). A different work by Jana & Sahu (2023b) determines the specific attributes of stablecoins, e.g., Tether, that are more efficient hedging instruments and safe-haven assets for the purpose of preventing the risks of the stock market. Comparatively, the capability of the remaining cryptocurrencies for the purpose of hedging and diversification remains more limited (Jana & Sahu, 2023b).

On the other hand, Jana & Sahu (2024) express a diverging opinion by asserting that cryptocurrencies are effective diversification or hedging instruments in normal market conditions but that the utility they provide is significantly reduced during financial crises (Jana & Sahu, 2024). The aforementioned opinion is corroborated by another work by the same authors that concludes that the inclusion of cryptocurrencies provides a shield to the

investor in normal market conditions but is unable to provide the same level of protection during crisis periods (Jana et al., 2024). Integrating cryptocurrencies into investment strategies requires a thorough understanding of market dynamics and risk management. Gapurbaeva et al. (2024) emphasize the importance of developing a strategic approach to cryptocurrency investments, including risk management practices to safeguard against potential losses (Gapurbaeva et al., 2024). Juškaitė and Gudelytė-Žilinskienė (2022) also highlight the necessity of conducting comprehensive studies to identify the benefits and risks associated with cryptocurrencies (Juškaitė & Gudelytė-Žilinskienė, 2022).

The role of cryptocurrencies as a hedge during periods of economic uncertainty is also documented. Eldomiaty and Khaled (2024) found that Bitcoin can serve as a safe-haven asset for investors during periods of extreme market volatility (Eldomiaty & Khaled, 2024). This makes cryptocurrencies particularly appealing to investors aiming to diversify their portfolios in uncertain economic environments.

One such prominent study is that of Alharbi et al. (2025), which examines the dynamic co-movement between stocks of Environmental, Social, and Governance (ESG) nature and green cryptocurrencies. The authors utilize state-of-the-art econometric models for the co-movement and hedging ability between these asset classes. The findings identify the presence of significant but varying over-time dependence between green cryptocurrencies and stocks of the ESG nature, pointing toward the intricateness of the relationship between the two asset classes. Green cryptocurrencies are not always good hedges for the volatility of stocks of the ESG nature unless the dynamic relationship between the asset classes is

appropriately addressed. The study adds to the body of knowledge of sustainable finance and calls for the examination of the over-time nature of asset relationships between the ESG and the cryptocurrency markets (Alharbi et al., 2025).

The study by Ali et al. (2024) looks at how green cryptocurrencies can play a role in portfolio diversification, as environmental concerns continue to grow and investors seek more sustainable options. The investigation has been conducted utilising advanced financial instruments, thereby facilitating the comparison of domestic and international financial markets. The findings indicate that incorporating green cryptocurrencies into investment portfolios can provide substantial diversification advantages, leading to enhanced stability and long-term sustainability for investors. The study identifies the capability of environmentally themed digital assets toward greener investments (Ali et al., 2024).

The continuous evolution of the cryptocurrency market creates new opportunities for portfolio optimization. Inci and Lagasse (2019) note that the contribution of various cryptocurrencies to the optimal portfolio can change over time, requiring constant re-evaluation of asset allocation (Inci & Lagasse, 2019). This dynamic nature of cryptocurrencies underscores the importance of adaptive investment strategies that respond to market changes.

Cryptocurrencies exhibited increased diversification advantages with the COVID-19 pandemic. Abdelmalek (2023) determines that including cryptocurrencies within portfolios enhances efficiency (Abdelmalek, 2023). Riahi et al. (2023) state that Bitcoin, Cardano, Ethereum, and Binance are good diversifiers while stablecoins such as Tether and USD

Coin are safe-haven assets (Riahi et al., 2023). Huang et al. (2023) reaffirm that under economic conditions of uncertainty, different types of cryptocurrencies are good for providing diversification advantages (Huang et al., 2023). The above are supplemented by the arguments of Xie et al. (2021), documenting that including stablecoins such as Tether helps protect more effectively compared to portfolios that contain solely Bitcoin or traditional assets such as gold (Xie et al., 2021). Moreover, cryptocurrencies may potentially undermine gold's role as a hedging instrument (Su et al., 2020).

Managing the high volatility of cryptocurrencies remains a key challenge in constructing optimal portfolios. Recent studies propose innovative approaches to address this issue. Just & Echaust (2024) find that the market volatility-reducing ability of Bitcoin is restricted (Just & Echaust, 2024). Gaies et al. (2024) utilize the frequency-domain analysis that explains that the short-horizon hedging of the short-term market conditions by the use of cryptocurrencies decreases over the medium horizon (Gaies et al., 2024). The above insight is consistent with that of Kurosaki & Kim (2022), using the models of GARCH for the mitigation of the high market volatility of the cryptocurrencies. The four largest cryptocurrencies are included by the latter using the portfolio optimization and the model of the generalized autoregressive conditional heteroskedasticity (GARCH), with the outcome that the Foster-Hart risk optimizing strategy produces more valuable portfolios compared with the conventional equal-weighted strategy (Kurosaki & Kim, 2022). Despite representing a substantial risk factor, the elevated volatility of cryptocurrencies also creates the potential for superior returns, rendering them attractive to

investors with higher risk appetites. (Almeida & Gonçalves, 2023; Chen, 2023).

Nuhiu et al. (2023) conducted an in-depth analysis of the relationship between the number of cryptocurrencies in a portfolio and overall diversification risk. Their findings reveal that increasing the number of cryptocurrencies in a portfolio reduces total risk; however, this effect exhibits diminishing returns beyond a certain threshold (Nuhiu et al., 2023). This conclusion is corroborated by Letho et al. (2022), who analysed mean returns and volatility, finding that cryptocurrencies can enhance the risk-return ratio for both traditional and alternative investments in emerging markets (Letho et al., 2022). These insights are particularly valuable for practical portfolio construction.

Schmitz and Hoffmann (2020) emphasize that cryptocurrencies offer diversification benefits, especially for investors who are underexposed to this emerging asset class (Schmitz & Hoffmann, 2020). The concept of diversification is further explored by Sinha and Yang (2021), who argue that including cryptocurrencies with smaller market capitalizations can lead to a positive reduction in risk, particularly under synchronized trading conditions (Sinha & Yang, 2021). This highlights the importance not only of the number of cryptocurrencies in a portfolio but also of their market characteristics. Similarly, Demiralay and Bayracı (2021) support this perspective, finding that different cryptocurrencies can add significant value to an investment portfolio, primarily through increasing returns rather than reducing risk (Demiralay & Bayracı, 2021).

Moreover, research recommends that to create an optimal cryptocurrency investment portfolio, investors should select uncorrelated cryptocurrencies, ensure adequate diversification to minimize risk, and focus

on liquid cryptocurrencies that can be easily exchanged for fiat currencies (Chen, 2023). Periodic rebalancing of the portfolio can also enhance its performance (Sadeqi, 2022; Saksonova & Kuzmina-Merlino, 2019).

Apart from traditional MPT models, recent research proposes different optimization techniques that account for the complexity and volatility of the cryptocurrency market. Chortane & Naoui (2025) address the application of Tsallis entropy and mutual information to optimize portfolios of cryptocurrencies in the hope of proposing an alternative for the mean-variance approach. Using the daily returns of the 2019–2024 periods of the S&P 500 and Bitwise 10 indices, the authors compare a number of models including the mean-variance (MV), the mean-entropy (ME), and the mean-mutual information (MI) models. The result of the research indicates that entropy models are superior to traditional models, particularly in terms of diversification and tail risk management during extreme market disruptions (Chortane & Naoui, 2025).

A significant contribution to cryptocurrency portfolio optimization methodologies lies in the integration of Minimum Spanning Tree (MST) analysis. MST provides a powerful tool for understanding interrelationships between cryptocurrencies and for optimizing portfolio structures. Initially applied to traditional financial markets by Onnela et al. (2003), MST enables the visualization and analysis of correlation structures between different assets (Onnela et al., 2003). The least correlated assets can be selected to construct optimal portfolios using the Markowitz model (Danko & Soltes, 2018). Jaureguizr Francés (2018) and Donmez et al. (2020) demonstrate how MST can be used to identify clusters of cryptocurrencies

with similar price behaviours, enabling more effective diversification (Jaureguizr Francés, 2018)(Donmez et al., 2020). An innovative extension of the traditional MST approach has been proposed by Kwapień et al. (2021), introducing the q -dependent detrended Minimum Spanning Tree (qMST) for analyzing correlation structures across different time scales. This method uncovers the evolution of cryptocurrency interrelationships over time, which is crucial for dynamic portfolio management (Kwapień et al., 2021).

Additionally, the MST approach has proven to be a reliable method for classifying cryptocurrencies into hierarchical clusters, which can inform investment strategies (Jaureguizr Francés, 2018). Such clustering helps investors identify which cryptocurrencies to include in their portfolios to achieve optimal diversification. Findings from these analyses suggest that investors should consider not only the expected returns of cryptocurrencies but also their correlations with other portfolio assets to enhance overall performance (Saksonova & Kuzmina-Merlino, 2019; Youssef et al., 2023).

The combination of Modern Portfolio Theory (MPT) and Minimum Spanning Tree (MST) analysis provides a robust framework for constructing cryptocurrency portfolios. By leveraging insights from MST about asset correlations and applying MPT principles, investors can create diversified portfolios that optimize risk and return. This approach is particularly relevant in the rapidly evolving cryptocurrency sector, where traditional investment strategies must adapt to the new behaviour of assets and market dynamics.

Incorporation of the cryptocurrencies into portfolios has the potential of possibilities and challenges due mainly to the latter's volatilities and varying market conditions. Despite the

prior work establishing that they are likely to enhance the portfolio diversity and the reward-risk quotient, areas of study remain for the examination of the latter over the long horizon, portfolio management under conditions of change, and the effect of macro conditions. The combination of Modern Portfolio Theory (MPT) and Minimum Spanning Tree (MST) analysis has proved to be an excellent framework for the maximization of crypto-inclusive portfolios by choosing assets with good but low-correlated returns.

3. Research Methodology

The object of the study is investment portfolios composed of traditional assets and cryptocurrencies. The subject is the impact of incorporating cryptocurrencies on the optimization of investment portfolios through the application of Modern Portfolio Theory (MPT) and Minimum Spanning Tree (MST) analysis. The scientific objective is to examine and substantiate the role of cryptocurrencies as a diversification tool in investment portfolios by assessing their effect on the risk-return ratio through the application of MPT and MST.

The research thesis posits that the inclusion of cryptocurrencies in investment portfolios composed of traditional assets leads to an improvement in the risk-return ratio while simultaneously offering opportunities for more effective diversification. By integrating Modern Portfolio Theory (MPT) with Minimum Spanning Tree (MST) analysis, portfolio structure can be optimized by identifying assets with low correlation and high returns. This makes cryptocurrencies a valuable instrument for risk management in contemporary financial strategies.

3.1. Data

The study focuses on the top 150 cryptocurrencies and leading market indices. Cryptocurrencies and indices are selected based on their market capitalization and data availability to ensure representativeness and comparability. Certain cryptocurrencies, such as SOL, DOT, SHIB, and UNI, are excluded due to insufficient data. Only assets with at least 50% data coverage for the selected period are included, resulting in a final list of 10 cryptocurrencies: BTC-USD, ETH-USD, BNB-USD, XRP-USD, ADA-USD, DOGE-USD, LTC-USD, MATIC-USD, TRX-USD, and LINK-USD. The stock indices used as benchmarks for portfolio performance comparison include:

- S&P 500 (GSPC)
- Dow Jones (DJI)
- NASDAQ Composite (IXIC)
- Russell 2000 (X.RUT)
- FTSE 100 (X.FTSE)
- Nikkei 225 (X.N225)
- DAX 30 (X.GDAXI)
- CAC 40 (X.FCHI)
- Hang Seng Index (X.HSI)
- SENSEX (X.BSESN)

The 50% coverage threshold was chosen to balance data scope and result reliability. The analysis covers data on cryptocurrencies and stock indices from May 8, 2019, to November 29, 2024. This nearly 5-year time frame provides a robust dataset for the study. While the selected period offers a solid foundation for analyzing long-term dependencies, it does not account for potential structural changes in the cryptocurrency market during this time.

Price data for cryptocurrencies and stock indices was sourced from Yahoo Finance using the `getSymbols()` function from the `quantmod` package in R. The data were stored as `xts` objects, which facilitates handling time series

efficiently. Following data pre-processing, daily logarithmic returns were calculated using the `Return.calculate()` function from the `PerformanceAnalytics` package. Closing prices were utilized to calculate daily returns using the formula for logarithmic returns:

$$r_t = \ln \left(\frac{P_t}{P_{t-1}} \right) \quad (1)$$

Where:

P_t : closing price per day t ,

P_{t-1} : is the price of the asset on the previous day.

r_t : logarithmic daily return.

The `na.locf()` method (Last Observation Carried Forward) is used to fill in missing values, carrying forward and backwards the last observed values to ensure the completeness of the time series. This approach ensures that missing data do not disrupt return calculations. Imputing missing values is a standard practice in time series processing, minimizing data loss while preserving data integrity.

3.2. Construction of correlation network

To analyze the relationships between assets, correlation matrices are calculated using a 30-day rolling window, specified by the `window_size` parameter in the `create_distance_matrix()` function. Constructing the correlation network through a rolling window and converting correlations into a distance matrix is an effective method for analyzing asset interconnections. The use of a Minimum Spanning Tree (MST) allows for the visualization of these relationships and the identification of key assets. The method for calculating correlations, `pairwise.complete.obs`, enables handling incomplete data within the window. Seasonal effects are not considered in this analysis, though they may

influence the dynamics of correlations. The correlation analysis, based on a 30-day rolling window identifies short-term dependencies between assets. This window length is appropriate as it balances sufficient statistical power and the ability to capture dynamic changes in market conditions. The correlation between two assets i and j is defined as:

$$\rho_{i,j} = \frac{\text{Cov}(r_i, r_j)}{\sigma_i \sigma_j} \quad (2)$$

Where:

$\text{Cov}(r_i, r_j)$: Covariance between asset returns i and j ,

$\sigma_i \sigma_j$: Standard deviations of returns on assets i and j .

Conversion to distance matrix:

The distance between two assets i and j is calculated as:

$$d_{i,j} = \sqrt{2(1 - \rho_{i,j})} \quad (3)$$

Where:

$\rho_{i,j}$: Is the correlation coefficient between assets i and j .

Transforming correlations into a distance matrix and constructing a Minimum Spanning Tree (MST) is an effective method for visualizing and analyzing relationships between assets. The centrality of assets within the MST is evaluated using closeness centrality, which provides insights into the significance of individual assets within the portfolio structure.

3.3. Minimum spanning tree (MST)

The minimum spanning tree (MST) is a subset of a graph that minimizes the total edge length while connecting all vertices. An MST is a graph that links all nodes (assets) using the minimum total weight of the connections (distances). The algorithm employed for constructing the MST is Kruskal's algorithm. Using Kruskal's algorithm ensures that the

Articles

total weight of the graph is minimized without introducing cycles. The calculated centrality is based on closeness centrality, implemented through the `closeness()` function. The MST is generated using the `mst()` function from the `igraph` package, with the distance matrix serving as edge weights.

Graph presentation:

- $G=(V,E)$: the graph, where V is the set of nodes (assets) and E is the set of edges (links between assets).
- $w_{ij}=D_{ij}$: weight of the rib between nodes i and j , which is equal to the distance between them.

The Kruskal algorithm:

1. Orders all edges E by increasing weight w_{ij} .
2. Selects the smallest edge that does not form a loop and adds it to the MST.
3. Repeat step 2 until all V nodes are connected.

Centrality in MST:

The closeness centrality, C_c , measures how central an asset is relative to others:

$$C_c(i) = \frac{1}{\sum_{j \neq i} d_{ij}}, \quad (4)$$

Where: d_{ij} is the minimum distance between nodes i and j .

- Top: Asset (cryptocurrency or index).
- Edge: Distance between assets d_{ij} .

The minimum spanning tree is defined as:

$$MST = \arg \min \sum_{i,j \in E} w_{i,j} \quad (5)$$

Where: $w_{i,j}=d_{i,j}$ are the edge weights.

Using the MST to study market structure and asset significance is a critical part of the methodology. Centrality in the MST, calculated via closeness centrality, provides valuable insights into the role of individual assets within the network.

Despite its utility, MST analysis has several limitations, including sensitivity to the choice of period, potential information loss from reducing complex interconnections, and the need for sufficiently long historical data.

3.4. Markowitz portfolio optimization theory

Optimization is based on minimizing risk for a given level of return or maximizing return for a fixed level of risk. The optimization is performed using the Markowitz model with regularization ($\lambda=10^{-4}$) to stabilize the covariance matrix. Regularization of the covariance matrix through the addition of a small parameter λ addresses potential stability issues, particularly when working with many assets or noisy data.

The choice of $\lambda=10^{-4}$ for covariance matrix regularization reflects a balanced approach between computational stability and preserving existing dependencies among assets. Some of the main reasons for this choice include:

- *Managing Matrix Instabilities:* Cryptocurrencies are highly volatile assets, and the covariance matrix can become singular or exhibit eigenvalues close to zero. Regularization with $\lambda=10^{-4}$ ensures that the matrix remains positive definite and stable for optimization.
- *Preserving Key Correlations:* Higher values of λ (e.g., $\lambda=1$ or more) can suppress important correlations between assets, distorting the analysis. $\lambda=10^{-4}$ offers an appropriate trade-off between stability and realistic representation of asset dependencies.
- *Empirical Observations:* Portfolio optimization literature frequently uses λ values ranging from $\lambda=10^{-1}$ to $\lambda=10^{-4}$, which

Articles

have proven effective for analyzing highly volatile assets.

- *Practical Convenience*: This value minimizes the risk of over- or under-regularization and enables portfolio optimization to retain the benefits of Markowitz theory while addressing instability issues.

The regularization of the covariance matrix, introduced via the parameter λ , plays a crucial role in portfolio optimization, particularly when dealing with volatile assets such as cryptocurrencies. Adding a regularization value to the diagonal of the covariance matrix enhances the stability of results and prevents numerical issues during optimization. The optimization is performed by solving a quadratic program to minimize risk for a fixed expected return. The process is implemented using the PortfolioAnalytics package with ROI.plugin.quadprog as the optimization backend. The goal is to determine the optimal asset weights (w_i) in the portfolio that minimize risk for a given level of expected return. The formalization is as follows:

The objective function for risk minimization:

$$\min_w w^T \Sigma w \quad (6)$$

Under restrictions:

$$\sum_i w_i = 1, w_i \geq 0 \quad (7)$$

Where:

- w : Vector of asset weights,
- Σ : Covariance matrix of returns,
- $\mu = [\mu_1, \mu_2, \dots, \mu_n]$: the vector of expected returns on assets,
- $\sum_i w_i = 1$: restriction on full investment,
- $w_i \geq 0$: non-negative weights.

The results (asset weights) are normalised to ensure that all weights are non-negative.

Expected Portfolio Returns:

$$\mu_p = \sum_i w_i \mu_i \quad (8)$$

Portfolio Risk:

$$\sigma_p = \sqrt{\sum_{i=1}^n \sum_{j=1}^n w_i w_j \sigma_{ij}} \quad (9)$$

Where: σ_{ij} is the covariance between assets.

The solution is found by quadratic optimization. A regularization $\lambda=10^{-4}$ is added to the covariance matrix to improve stability:

$$\Sigma_{reg.} = \Sigma + \lambda I, \quad (10)$$

Where: I is the unitary matrix.

3.5. Comparison to benchmark portfolios

The optimal portfolio is compared to benchmark portfolios (e.g., S&P 500). The difference in returns between the optimal portfolio and the benchmark portfolios is analysed using the Wilcoxon test:

$$H_0: \text{Median of the difference} = 0 \quad (11)$$

This comparison, based on the Wilcoxon test, provides a reliable statistical tool for evaluating differences in return distributions. The density distribution of returns is visualized using `geom_density()`, facilitating a comparison between portfolio types. The returns of the optimal portfolio are compared to stock indices using the Wilcoxon test. The benchmark includes the average return of the top 5 stock indices (e.g., S&P 500, Dow Jones).

The methodology combines statistical, graph-based, and optimization approaches, enabling an in-depth analysis of the cryptocurrency market. This integration leads to the creation of efficient portfolios capable of delivering competitive returns compared to traditional assets.

4. Results

The analysis reveals dynamic dependencies between assets and

demonstrates how innovative methodologies such as the Minimum Spanning Tree and Markowitz theory can be applied for portfolio optimization. Each component of the analysis provides significant insights into asset behaviour, volatility, and opportunities for effective risk management.

4.1. Data analysis and returns

Calculated daily logarithmic returns play a crucial role in understanding volatility and long-term trends in asset behaviour. Logarithmic returns clearly highlight the differences between assets. Stock indices such as the S&P 500 and Dow Jones exhibit stable annual returns of 6%–8% with low risk levels (10%–12%). In contrast, cryptocurrencies like DOGE-USD and MATIC-USD demonstrate returns ranging between 20%–30%, but with risks exceeding 50%–60%. This disparity underscores cryptocurrencies' potential for high returns, but also their significant

volatility, which complicates their integration into traditional portfolios.

Figure 1 illustrates the trade-off between risk and return, demonstrating that higher-risk assets (DOGE-USD, MATIC-USD) offer higher expected returns but also a greater likelihood of losses.

4.2. Correlation matrix and distance matrix (MST)

Figure 2 illustrates the correlations between assets based on daily logarithmic returns. The strong correlation between BTC-USD and ETH-USD, exceeding 0.85, confirms their close interconnection within the crypto ecosystem. This high correlation explains the central role of these assets in the portfolio and highlights their stability. Conversely, assets like DOGE-USD and TRX-USD exhibit weaker correlations with other components (below 0.4), indicating their potential for diversification and risk reduction.



Fig. 1. Risk vs. return

Source: Author's calculations based on data from Yahoo Finance (2020–2024).

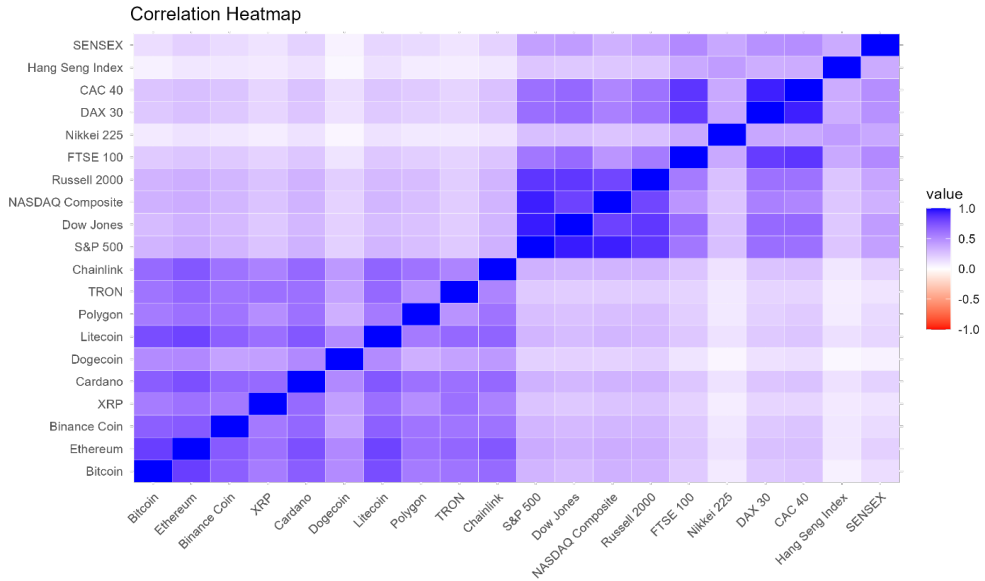


Fig. 2. Correlation heat map

Source: Author’s own elaboration based on empirical price correlation analysis.

Figure 2 reveals strong positive correlations among stock indices, highlighting the limited diversification in portfolios that exclude cryptocurrencies. This reduces the potential for overall risk mitigation through the inclusion of low-correlation assets.

The heatmap visualizes these relationships using colour gradients to represent the correlations between assets. Transforming correlation matrices into distances and subsequently constructing a Minimum Spanning Tree (MST) provides additional insights into the structural dependencies among assets.

Transforming correlation matrices into distance matrices and subsequently constructing a Minimum Spanning Tree (MST) adds a structural dimension to the analysis. Figure 3 presents the MST, which reveals a compact structure dominated by the connections between stock indices. This structure, based on the distance matrix,

converts the correlation dependencies between assets into a graphical form.

The edge weights, which reflect the "distance" between assets, provide valuable insights into the structural relationships within the portfolio and can guide portfolio optimization. The weights in the MST indicate:

- *Relationships Between Assets:* In the MST, the weight of each edge represents the inverse of the correlation between assets. Lower weights indicate stronger correlations, signifying that the assets exhibit similar behaviour or reactions to market conditions. For example, the low weight between BTC-USD and ETH-USD indicates their strong correlation, emphasizing their proximity within the crypto ecosystem. This suggests limited diversification benefits between these two assets.

Minimum Spanning Tree (MST)

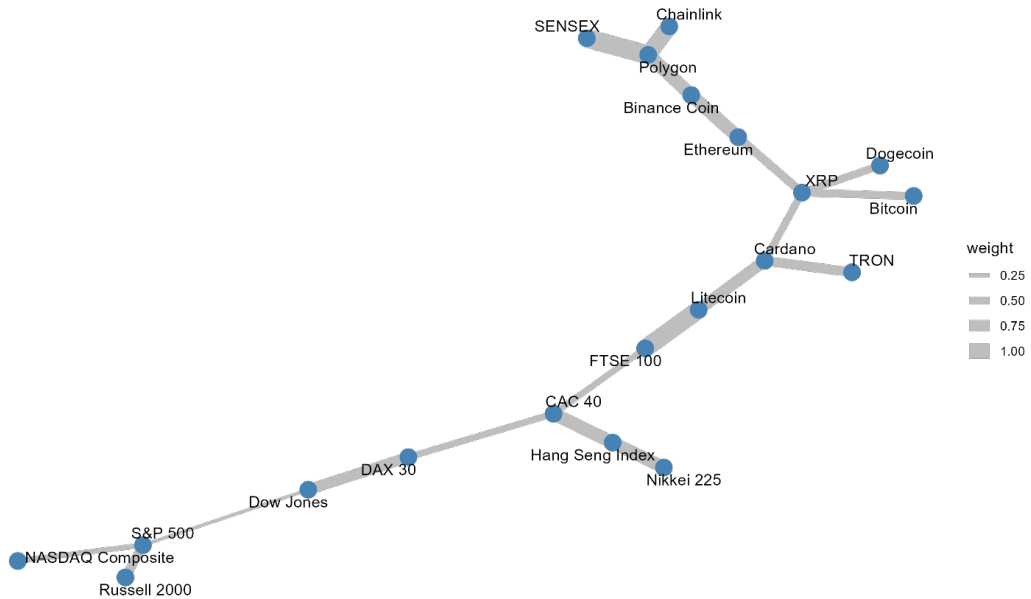


Fig. 3. Minimum Spanning tree

Source: Compiled by the author using Minimum Spanning Tree (MST) ana R software.

- **Asset Centrality:** Assets with the most connections (i.e., those linking the highest number of other nodes) play a central role in the network. In the MST for traditional assets, stock indices such as the S&P 500 and Dow Jones occupy central positions due to their high interdependence. This makes them critical for understanding overall portfolio risk in traditional settings. Conversely, assets with weaker connections, such as TRX-USD and DOGE-USD, are peripheral but offer diversification potential.
- **Identifying Leaders and Peripheral Assets:** Each MST highlights assets that act as "bridges" in the network (leaders) and those that are weakly connected (peripheral). For instance, crypto assets located on the network's periphery, such as DOGE-USD and ADA-USD, have fewer connections with traditional indices. This underscores their potential role in reducing overall portfolio risk when included.
- **Revealing Homogeneity and Clusters:** The MST reveals clusters of assets with similar behaviour. For example, traditional stock indices form a tightly connected cluster with low edge weights, indicating their homogeneity. In contrast, cryptocurrencies often form a separate cluster or remain peripheral. This distinction highlights the potential for increased diversification by combining assets from different clusters.
- **Changes Over Time and MST Adaptability:** The edge weights in the MST can change over time, reflecting the dynamic nature of market conditions. For example, during periods of high volatility, certain assets like BTC-USD may become more strongly correlated with traditional indices, increasing the edge weights in the network. Monitoring these changes provides

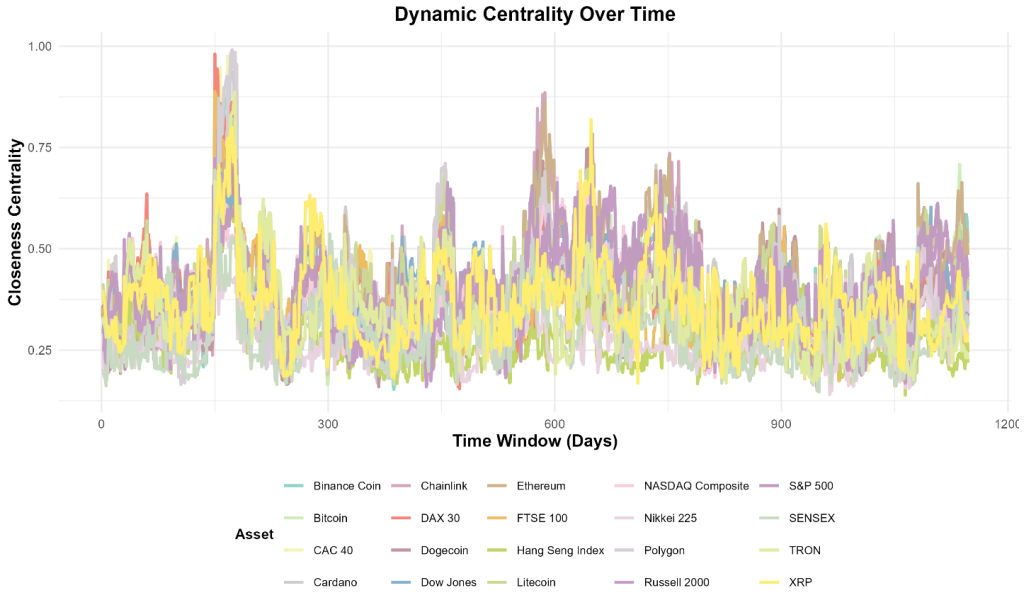


Fig. 4. Dynamics of centrality

Source: Author's own elaboration based on temporal network centrality calculations.

valuable insights into the adaptability of portfolio strategies.

The MST facilitates portfolio optimization by offering insights into how assets interact. Edge weights guide the selection of low-correlation assets (and therefore assets with greater "distance"). An optimal portfolio balances strongly connected assets, which contribute to stability, with peripheral assets, which enhance diversification.

The presence of peripheral crypto assets with low correlations (high edge weights) offers opportunities to reduce risk, even though these assets may exhibit higher volatility. This is particularly valuable during crises when traditional assets tend to move synchronously, increasing overall portfolio risk. Therefore, the MST provides a strategic framework for making informed decisions when constructing a resilient and diversified portfolio.

Figure 4 provides a temporal perspective on asset significance within the network by visualizing their dynamic centrality. BTC-USD and ETH-USD consistently maintain high centrality values across most time windows, demonstrating stability and their key role within the crypto ecosystem. Conversely, assets like DOGE-USD and TRX-USD exhibit significant fluctuations, making them better suited for tactical strategies aimed at short-term returns. This distinction between stable long-term assets and tactical investment opportunities enables more effective portfolio structuring.

The relationship between the correlation matrix, the MST, and portfolio optimization is critical for constructing an optimal portfolio. Correlation dependencies guide selecting low-correlation assets that reduce risk. The MST, in turn, helps identify structural dependencies and asset centrality within

the network. Combining these methods with portfolio optimization enables the creation of a diversified portfolio that effectively balances risk and return.

4.3. Portfolio optimization according to Markowitz theory

The portfolio optimization results, visualized in Figure 5, indicate that the optimal portfolio excludes cryptocurrencies, assigning them zero weights. Figure 6 further shows that the optimal portfolio aligns more closely with traditional assets, lacking the additional returns that crypto assets could potentially contribute. The zero weights assigned to cryptocurrencies in the portfolio carry significant implications for the analysis. First, this outcome suggests that the optimization model favours traditional assets such as stock indices (e.g., S&P 500 and Dow Jones) over the more volatile crypto assets. Cryptocurrencies such as BTC-USD, ETH-USD, and DOGE-USD are theoretically

considered instruments with high return potential but significant risk. However, when applying Markowitz’s theory—which seeks to minimize risk at a given level of return—these assets are automatically excluded from the optimal portfolio, as their contribution to overall risk outweighs their potential benefits in terms of returns.

One primary reason for this result is the extreme volatility of cryptocurrencies. High standard deviation values (exceeding 50%–60% for assets like DOGE-USD and MATIC-USD) significantly elevate the risk of the entire portfolio. Even though these assets offer impressive expected annual returns between 20% and 30%, the model prioritizes minimal risk, favouring assets with more stable characteristics. In this context, stock indices like S&P 500 and Dow Jones, which exhibit lower risk levels (10%–12%) and

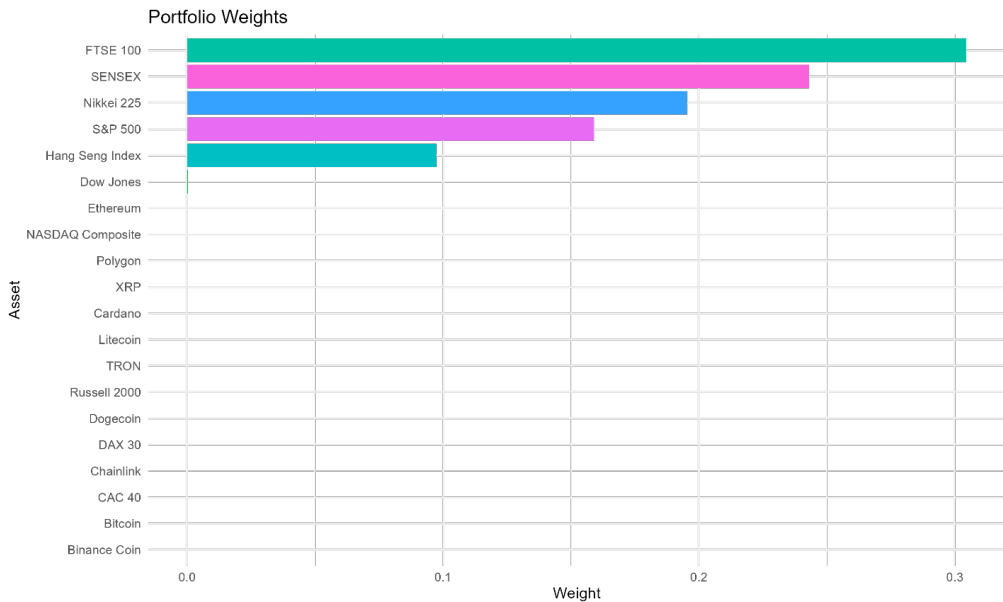


Fig. 5. Portfolio weights

Source: Author’s own elaboration via Markowitz portfolio optimization.



Fig. 6. Efficient frontier.

Source: Author's own construction based on Modern Portfolio Theory (MPT) optimization.

moderate annual returns of around 6%–8%, are preferred for inclusion in the optimal portfolio.

Another possible explanation for the zero weights assigned to crypto assets is their correlation structure. While cryptocurrencies like BTC-USD and ETH-USD exhibit high intra-crypto correlations (above 0.85), their weak correlations with traditional assets suggest potential diversification benefits. However, their extreme volatility diminishes these advantages under a risk-averse framework. Consequently, the optimization excludes them as "inefficient" assets.

These findings highlight the challenges of integrating cryptocurrencies into traditional portfolios with risk-averse optimization models. The extreme volatility of crypto assets and their limited diversification benefits under Markowitz's framework result in their exclusion in favour of more stable and predictable traditional assets. The following

section compares the performance of the optimized portfolio against benchmark indices to evaluate its practical relevance.

4.4. Comparison with benchmark portfolios

Figure 7 illustrates that the optimal portfolio achieves comparable results to benchmarks such as the S&P 500 and Dow Jones. The average return is 6.8%, which is equal to or slightly lower than that of the benchmarks. The portfolio's risk is approximately 12%, reflecting its stability.

Results from the Wilcoxon test indicate that differences in return distributions between the optimal portfolio and the benchmark indices are not statistically significant ($p > 0.05$). This suggests that, despite the optimal portfolio's slightly higher return, it does not significantly outperform traditional stock indices while assuming greater risk.

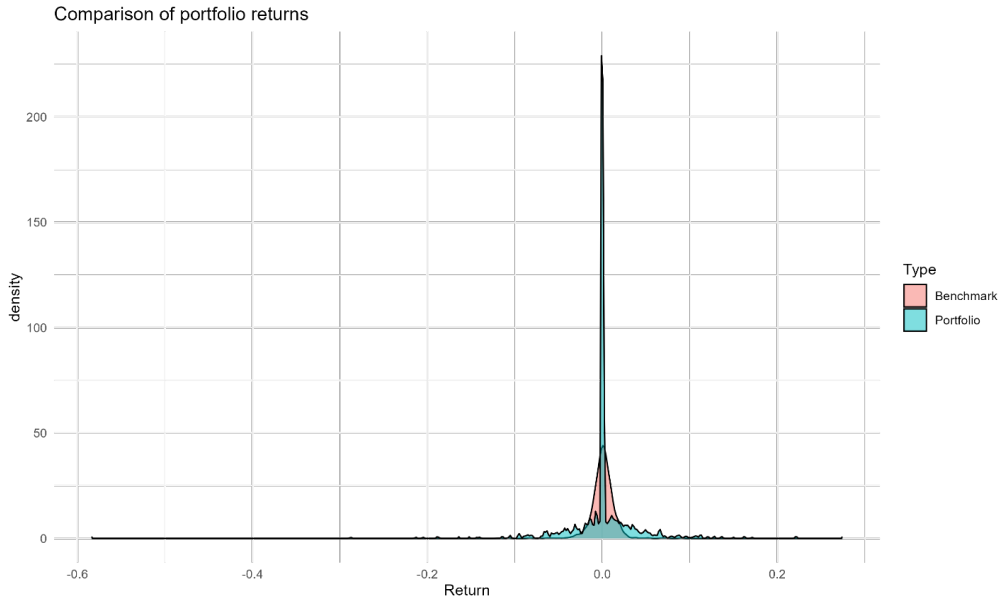


Fig. 7. Return comparison: Portfolio vs. benchmark

Source: Author's calculations comparing the optimal portfolio against S&P 500 and Dow Jones benchmarks.

The exclusion of cryptocurrencies from the optimal portfolio highlights two key considerations:

- *Compromised Potential for High Returns:* The exclusion results in a compromise, as returns of 8.67% with a risk of 15.27% remain unrealized, reflecting the underutilization of crypto assets' full potential for generating high returns.
- *Limitations of a Static Markowitz Framework:* The zero weights assigned to cryptocurrencies reflect the limitations of the static approach inherent in Markowitz's theory. The high volatility of these assets suggests the need for a dynamic and adaptive approach to their inclusion in the portfolio. Dynamic analysis, as incorporated in the calculation of correlations and MST (Minimum Spanning Tree), provides contextual updates on risk

and interrelationships between assets, mitigating the static nature of the model.

The obtained results demonstrate that the use of Modern Portfolio Theory (MPT) for portfolio optimization constantly leaves cryptocurrencies outside the efficient frontier due to their volatility. This tendency is particularly strong for assets such as DOGE-USD and MATIC-USD, whose returns are followed by standard deviations of over 50-60%. Such assets can lead to high returns, but they are ruled out by the classical Markowitz model, as it seeks risk minimization in the mean-variance framework.

Minimum Spanning Tree (MST) analysis confirms that cryptocurrencies are mostly in peripheral positions in the correlation network, which suggests that adding them may enhance diversification efficiency—on

the condition that other risk management strategies are embraced.

Due to the high volatility of cryptocurrencies and their dynamic correlation with traditional assets, static MPT models are not able to capture portfolio risk profile evolution over time. This calls for the need to adopt dynamic risk management approaches, which are capable of adjusting portfolio structures in line with the evolution of volatility and correlations.

One of the technical strategies being considered is dynamic rebalancing, which involves periodically adjusting the mix of assets in the portfolio to maintain the desired balance and adapt to changes in the financial market. If for example, a certain cryptocurrency asset that is believed to have a low correlation with traditional assets suddenly begins correlating to the S&P 500 index during a cooldown market phase, with dynamic rebalancing, the asset's exposure could be reduced. Alongside that, the increase in volatility risk can be offset by increasing the amount of stable assets. Through this the portfolio would still have the desired level of effectiveness even when crypto assets are not stable.

Another useful effective tool for risk management based on the results is an options or futures hedging strategy for cryptocurrency trading. For example, the results show that Bitcoin and Ethereum have a strong internal relationship (greater than 0.85). This means that if one of the assets declines, the other one is very likely to do the same. This creates an opportunity for investors to use options as a way to protect against potential losses. By purchasing put options on these assets, investors can set a limit on how much they might lose if the asset's price drops sharply.

As a part of a strategy to mitigate exposure to volatility, futures contracts can be used as well. For instance, an investor who is long on

Bitcoin can gain some protection from price declines by assuming a short futures position on the same asset. This would allow some degree of market participation while limiting risk exposure to a reasonable level.

Employing techniques such as hedging or risk mitigation through derivative instruments could allow for better control of volatility and more effective integration of cryptocurrencies. The use of hedging tools such as options and/or futures could also help balance the high risk of cryptocurrencies while maximizing potential returns. According to Huang (2024), using dynamic methods to regulate the market, such as hedging strategies, could help reduce potential losses by as much as 50% during extreme market conditions. Few investigations conducted using modern risks like Value at Risk or Conditional Value at Risk have validated this statement (Văduva, 525; Bodnar et al., 2022).

Yet another critical finding is that cryptocurrencies have diverse and changing correlation features, which suggests that their contribution to portfolios is not static but rather flexible. The dynamic utilization of adaptive optimization offers improved exposure control to cryptocurrencies using time series correlation analysis.

One such method is dynamic selection which is cryptocurrency centred and is based on the Minimum Spanning Tree (MST) in which these currencies are added in the portfolio only when their correlation with other assets is low. For instance, during a certain period if Dogecoin is shown to have low correlation with other traditional investment indices, then it can be added for diversification purposes. If the opposite occurs, then the adaptive optimization can be set to minimize the amount, thus maintaining the effectiveness of the said strategy.

Moreover, ML (machine learning) models can be used to forecast volatility and re-weight the portfolios accordingly. For example, neural networks use historical cryptocurrency data to predict the likelihood of volatility spikes, allowing investors to lower their stakes in risky assets before such events occur. This will help better manage low and high-risk crypto investments over the long run.

To summarize these conclusions, the outcomes of the research have surpassed expectations in the context of the crypto market, especially proving that static optimization does not work. These results indicate that there is no “magic bullet” which will resolve the issue of high volatility and non-stationary correlations. There's also evidence that incorporating cryptocurrencies into modern portfolios designed in accordance with MPT will not have any material impact on the risk-adjusted return. Still, the MST results suggest that the position of cryptocurrencies in the asset network is more exceptional than primary. It means that these assets can enhance diversification but are peripheral to the asset network and only as such are useful if they are actively managed.

This conclusion highlights the importance of adopting dynamic risk management techniques to allow for a more flexible inclusion of crypto assets in investment portfolios. By using hedging strategies, such as derivatives, investors can reduce the negative impact of price volatility. Additionally, approaches like periodic rebalancing and predictive modelling can help integrate cryptocurrencies more effectively into long-term investment plans, providing better control and stability. This increases the possibilities available to investors as they can participate in the controlled risks associated with cryptocurrencies and take advantage of its high returns.

5. Discussion

The study demonstrates that, despite their potential for substantial returns, cryptocurrencies such as DOGE-USD and MATIC-USD are frequently excluded from optimal portfolios constructed using traditional Modern Portfolio Theory (MPT). This exclusion is primarily attributed to their extreme volatility, which poses significant challenges within static optimization frameworks. Such models inherently prioritize risk minimization over return maximization, making it difficult to incorporate highly volatile assets like cryptocurrencies. Additionally, minimum spanning tree (MST) analysis reveals that these digital assets occupy peripheral positions in the asset correlation network, suggesting limited diversification benefits within conventional portfolio structures. Collectively, these findings underscore the need to reassess traditional optimization methodologies to accommodate the unique characteristics of cryptocurrencies.

These results align with prior research characterizing cryptocurrencies as high-risk, high-return assets with minimal correlation to traditional financial instruments (Brière et al., 2015; Wang, 2023). However, this study advances the literature by illustrating how extreme volatility effectively precludes cryptocurrencies from inclusion in optimal portfolios under MPT frameworks. This conclusion contrasts with earlier studies that suggested cryptocurrencies could enhance portfolio performance through diversification benefits (Ma et al., 2020; Katsiampa et al., 2022). The divergence likely stems from methodological differences, particularly the application of MST analysis to evaluate asset correlations and centrality within portfolio networks.

The implications of these findings are noteworthy for both practitioners and academics. For investors and financial advisors, the study highlights that static portfolio optimization models may not adequately account for the distinctive risk-return profiles of cryptocurrencies. Instead, dynamic risk management strategies capable of adapting to evolving market conditions and asset correlations are essential. On a theoretical level, the findings suggest the necessity of revising traditional portfolio optimization frameworks to integrate emerging asset classes with unconventional characteristics. Furthermore, for policymakers, the results emphasize the importance of crafting regulatory frameworks that balance innovation in digital assets with measures to protect investors.

Several limitations of the study should be acknowledged. The analysis relies on historical data spanning from 2019 to 2024, which may not fully capture the range of market conditions influencing cryptocurrency performance. Additionally, the exclusion of certain cryptocurrencies due to data availability constraints may limit the generalizability of the findings. Moreover, the static nature of the MPT model employed does not account for the dynamic correlations and volatility clustering often observed in cryptocurrency markets. Finally, the study focuses predominantly on quantitative analysis, omitting behavioural and macroeconomic factors that could influence cryptocurrency adoption and market dynamics.

Future research should explore several promising directions. Longitudinal studies examining how the integration of cryptocurrencies into investment portfolios evolves alongside market maturation could yield valuable insights. The incorporation

of machine learning techniques to predict cryptocurrency price movements and dynamically optimize portfolio weights may enhance the practical applicability of portfolio models. Additionally, investigating the impact of regulatory developments on the integration of cryptocurrencies into portfolios would address a critical gap in the literature. Research into sustainable investment frameworks for cryptocurrencies could further contribute to the development of socially responsible strategies for digital assets.

6. Cryptocurrencies in Portfolio Optimization: Conclusions, Challenges, and Future Research Directions

This study focuses on cryptocurrencies and their effects on the investment portfolios optimizations containing digital and conventional assets using the MPT and MST analysis. The research thesis postulated is that the risk-return ratio and the diversification ratio can be improved by the introduction of cryptocurrencies. The methodology used for the study is quantitative as the objective is to assess the effect of volatility and correlation of crypto assets on the structure of the optimal portfolios.

The main findings of the study reveal the intricate trade-off between opportunities and constraints. Correlation analysis shows that certain cryptocurrencies have a low correlation with other traditional instruments, hence they can be utilized for the general risk diversification of the portfolio. On the other hand, the high level of dependence of major crypto assets such as Bitcoin and Ethereum on each other reduces the opportunity for diversification in the crypto asset class.

Standard MPT models have excluded DOGE-USD and MATIC-USD from the efficient

frontier based on their high volatility. These models tend to prefer low risk assets. MST analysis corroborates the marginal position of cryptocurrencies in the hierarchy of assets, noting their utility for further diversification while cautioning that their risks are relatively high. These findings contradict the initial research hypothesis, as cryptocurrencies do not improve the risk-return profile under static, low-risk-tolerant optimization models.

Unlike existing traditional assets such as S&P 500 and Dow Jones that are balanced yet do not provide much flexibility in returns, these provide high volatility opportunities. They are no doubt very attractive, but the risk they pose to the overall portfolio makes them too conservative to be used in a diversified portfolio. This highlights the weaknesses of static models when analysing volatile assets.

Dynamic risk management strategies enable the continuous rebalancing of portfolios in response to changing market conditions and cryptocurrency volatility. Given the high volatility of these assets, investors should employ hedging instruments such as options and futures contracts to mitigate downside risk. This would reduce the overall risk to the portfolio, allowing investments to benefit from the anticipated high returns that cryptocurrencies offer without exposing themselves to high risk at the same time.

The adoption of cryptocurrencies into investment portfolios and the use of these digital currencies would be made easier through incorporating markets where correlate changes and trends are the basis for dynamic models. These systems are crucial in volatile environments because they ensure relevance to current affairs. While strict limits are often imposed on the allocation of highly volatile cryptocurrencies in traditional portfolios, a more flexible approach to including higher-

risk assets can significantly enhance diversification and improve overall portfolio returns.

When assessing the interrelations of investment assets, portfolio managers are able to identify cryptocurrencies that are not highly linked to traditional assets, resulting in portfolios that are better diversified and reduce the risk of unexpected changes in the market. Understanding the use of cryptocurrencies can help overcome the challenges they present to financial markets and equip regulators with valuable insights for designing balanced regulatory policies. Investors looking to make the most of the massive profits that can be made from cryptocurrencies may try to limit their losses through methods such as periodic rebalancing and stop-loss orders.

Future research should aim to create more sophisticated risk management frameworks that incorporate shifting asset correlations over time and analyse the use of instruments to deal with the volatility of cryptocurrencies. The application of ML and neural networks for predicting cryptocurrency prices may help to enhance a more accurate investment strategy taking into consideration the multilateral nature of the market. Also, empirically investigating macroeconomic conditions and their effects on the usefulness of crypto assets for portfolio diversification may open new avenues for improving investment strategies.

This research depicts the multifaceted reality of cryptocurrencies as an investment asset, exposing their merits and demerits in a traditional investment portfolio. MPT aligned with MST contributes an understanding of the limitations not only of these models, but also of the opportunity posed by cryptocurrencies as effective risk measures. In the future, using flexible investment strategies and advanced analysis techniques will be crucial for

successfully integrating cryptocurrencies into investment practices. These methods will help strike a balance between risk and return, even in the face of significant market uncertainty.

References

- Abdelmalek, W. (2024). Cryptocurrencies and portfolio diversification before and during COVID-19. *EuroMed Journal of Business*, 19(4), 1084–1120.
- Alharbi, S. S., Naveed, M., Ali, S., & Moussa, F. (2025). Sailing towards sustainability: Connectedness between ESG stocks and green cryptocurrencies. *International Review of Economics & Finance*, 98, 103848.
- Ali, F., Khurram, M. U., Sensoy, A., & Vo, X. V. (2024). Green cryptocurrencies and portfolio diversification in the era of greener paths. *Renewable and Sustainable Energy Reviews*, 191, 114137.
- Almeida, J., & Gonçalves, T. C. (2023). Portfolio Diversification, Hedge and Safe-Haven Properties in Cryptocurrency Investments and Financial Economics: A Systematic Literature Review. In *Journal of Risk and Financial Management* (Vol. 16, Issue 1). <https://doi.org/10.3390/jrfm16010003>
- Andrianto, Y. (2017). The Effect of Cryptocurrency on Investment Portfolio Effectiveness. *Journal of Finance and Accounting*, 5(6). <https://doi.org/10.11648/j.jfa.20170506.14>
- Bodnar, T., Niklasson, V., & Thorsén, E. (2022). Volatility sensitive Bayesian estimation of portfolio VaR and CVaR. arXiv preprint arXiv:2205.01444.
- Brauneis, A., & Mestel, R. (2019). Cryptocurrency-portfolios in a mean-variance framework. *Finance Research Letters*, 28. <https://doi.org/10.1016/j.frl.2018.05.008>
- Brière, M., Oosterlinck, K., & Szafarz, A. (2015). Virtual currency, tangible return: Portfolio diversification with bitcoin. In *Journal of Asset Management* (Vol. 16, Issue 6). <https://doi.org/10.1057/jam.2015.5>
- Bruhn, P., & Ernst, D. (2022). Assessing the Risk Characteristics of the Cryptocurrency Market: A GARCH-EVT-Copula Approach. *Journal of Risk and Financial Management*, 15(8). <https://doi.org/10.3390/jrfm15080346>
- Cheng, H. P., & Yen, K. C. (2020). The relationship between the economic policy uncertainty and the cryptocurrency market. *Finance Research Letters*, 35. <https://doi.org/10.1016/j.frl.2019.101308>
- Chen, S. (2023). The Implementation of Modern Portfolio Theory on New Financial Assets: Evidence from Cryptocurrencies. *Advances in Economics, Management and Political Sciences*, 56(1). <https://doi.org/10.54254/2754-1169/56/20231149>
- Chortane, S. G., & Naoui, K. (2025). The End of Mean-Variance? Tsallis Entropy Revolutionises Portfolio Optimisation in Cryptocurrencies. *Journal of Risk and Financial Management*, 18(2), 1–30.
- Ćosić, K., & Časni, A. Č. (2019). The impact of cryptocurrency on the efficient frontier of emerging markets. *Croatian Review of Economic, Business and Social Statistics*, 5(2). <https://doi.org/10.2478/crebss-2019-0012>
- Danko, J., & Soltes, V. (2018). Portfolio creation using graph characteristics. *Investment Management and Financial Innovations*, 15(1). [https://doi.org/10.21511/imfi.15\(1\).2018.16](https://doi.org/10.21511/imfi.15(1).2018.16)
- Danko, J., Šoltés, V., & Bindzár, T. (2020). New approach to portfolio creation using the minimum spanning tree theory and its robust evaluation. *Quality Innovation Prosperity*, 24(2). <https://doi.org/10.12776/QIP.V24I2.1450>

- Demiralay, S., & Bayraci, S. (2021). Should stock investors include cryptocurrencies in their portfolios after all? Evidence from a conditional diversification benefits measure. *International Journal of Finance and Economics*, 26(4). <https://doi.org/10.1002/ijfe.2116>
- Donmez, C. Ç., Dereli, A. F., Horasan, M. Bilal, & Yildiz, C. (2020). AN ANALYSIS OF EVOLUTIONARY CRYPTOCURRENCY MARKET DYNAMICS. *Elektronik Sosyal Bilimler Dergisi*, 19(74). <https://doi.org/10.17755/esosder.554146>
- Eldomiaty, T. and Khaled, N. (2024). Cryptocurrency volatility and egyptian stock market indexes: a note. *Modern Finance*, 2(1), 121-130. <https://doi.org/10.61351/mf.v2i1.138>
- Gaies, B., Chaâbane, N., & Bouzouita, N. (2024). Navigating the storm: Time-frequency quantile dependence and non-linear causality between cryptocurrency market volatility and financial instability. *The Quarterly Review of Economics and Finance*, 93, 43–70.
- Gapurbaeva, S., Savina, S., Dzhaliilova, L., Tadzhibaeva, T., & Tokoev, B. (2024). International river and sea transportation: specifics of risk management in cryptocurrency transactions. *BIO Web of Conferences*, 107, 04006. <https://doi.org/10.1051/bioconf/202410704006>
- Hong, M. Y., & Yoon, J. W. (2022). The impact of COVID-19 on cryptocurrency markets: A network analysis based on mutual information. *PLoS ONE*, 17(2 February). <https://doi.org/10.1371/journal.pone.0259869>
- Huang, G., Zhou, X., & Song, Q. (2024). Dynamic optimization of portfolio allocation using deep reinforcement learning. *arXiv*. <https://arxiv.org/abs/2412.18563>
- Huang, X., Han, W., Newton, D., Platanakis, E., Stafylas, D., & Sutcliffe, C. (2023). The diversification benefits of cryptocurrency asset categories and estimation risk: pre and post Covid-19. *The European Journal of Finance*, 29(7), 800–825.
- Inci, A. C., & Lagasse, R. (2019). Cryptocurrencies: applications and investment opportunities. *Journal of Capital Markets Studies*, 3(2). <https://doi.org/10.1108/JCMS-05-2019-0032>
- Jacobs, G. (2018). Cryptocurrencies & the Challenge of Global Governance. *Cadmus*, 3(4).
- Jana, S., & Sahu, T. N. (2023a) Can diversification be improved by using cryptocurrencies? Evidence from Indian equity market. *Journal of Financial Economic Policy*, 15(6), 551–573.
- Jana, S., & Sahu, T. N. (2023b). Is the cryptocurrency market a hedge against stock market risk? A Wavelet and GARCH approach. *Economic Notes*, 52(3), e12227.
- Jana, S., & Sahu, T. N. (2024). A wavelet analysis of investing in cryptocurrencies in the Indian stock market. *International Journal of Emerging Markets*.
- Jana, S., Nandi, A., & Sahu, T. N. (2024). Can cryptocurrencies provide better diversification benefits? Evidence from the Indian stock market. *Journal of Interdisciplinary Economics*, 02601079231214859.
- Jaureguizr Francés, C. (2018). The cryptocurrency market: A network analysis. *ESIC Market Economics and Business Journal*, 49(3). <https://doi.org/10.7200/esicm.161.0493.4>
- Juškaitė, L., & Gudelytė-Žilinskienė, L. (2022). INVESTIGATION OF THE FEASIBILITY OF

Articles

- INCLUDING DIFFERENT CRYPTOCURRENCIES IN THE INVESTMENT PORTFOLIO FOR ITS DIVERSIFICATION. *Business, Management and Economics Engineering*, 20(1). <https://doi.org/10.3846/bmee.2022.16883>
- Just, M., & Echaust, K. (2024). Cryptocurrencies against stock market risk: New insights into hedging effectiveness. *Research in International Business and Finance*, 67, 102134.
- Katsiampa, P., Yarovaya, L., & Zięba, D. (2022). High-frequency connectedness between Bitcoin and other top-traded crypto assets during the COVID-19 crisis. *Journal of International Financial Markets, Institutions and Money*, 79. <https://doi.org/10.1016/j.intfin.2022.101578>
- Kurosaki, T., & Kim, Y. S. (2022). Cryptocurrency portfolio optimization with multivariate normal tempered stable processes and Foster-Hart risk. *Finance Research Letters*, 45. <https://doi.org/10.1016/j.frl.2021.102143>
- Kwapien, J., Wątopek, M., & Drożdż, S. (2021). Cryptocurrency market consolidation in 2020–2021. *Entropy*, 23(12). <https://doi.org/10.3390/e23121674>
- Letho, L., Chelwa, G., & Alhassan, A. L. (2022). Cryptocurrencies and portfolio diversification in an emerging market. *China Finance Review International*, 12(1). <https://doi.org/10.1108/CFRI-06-2021-0123>
- Li, X., & Wang, C. A. (2017). The technology and economic determinants of cryptocurrency exchange rates: The case of Bitcoin. *Decision Support Systems*, 95. <https://doi.org/10.1016/j.dss.2016.12.001>
- Markowitz, H. (1952). Portfolio Selection. *Journal of Finance*. In Markowitz HM—1952.
- Ma, Y., Ahmad, F., Liu, M., & Wang, Z. (2020). Portfolio optimization in the era of digital financialization using cryptocurrencies. *Technological Forecasting and Social Change*, 161. <https://doi.org/10.1016/j.techfore.2020.120265>
- Nuhui, A., Aliu, F., Horák, J., & Peci, B. (2023). Making Informed Decisions in the Volatile Crypto Market: An Analysis of Portfolio Risk and Return. *SAGE Open*, 13(3). <https://doi.org/10.1177/21582440231193600>
- Onnela, J. P., Chakraborti, A., Kaski, K., Kertész, J., & Kanto, A. (2003). Asset Trees and Asset Graphs in Financial Markets. *Physica Scripta T*, 106. <https://doi.org/10.1238/physica.topical.106a00048>
- Riahi, R., Bennajma, A., Jahmane, A., & Hammami, H. (2024). Investing in cryptocurrency before and during the COVID-19 crisis: Hedge, diversifier or safe haven? *Research in International Business and Finance*, 67, 102102.
- Risk.net. (2024, August 22). Value at Risk (VaR). Retrieved from <https://www.risk.net/type/technical-paper/topics/value-at-risk-var>
- Sadeqi, H. (2022). A Second-Order Hierarchical Clustering of Cryptocurrencies. *Iranian Journal of Management Studies*, 15(3). <https://doi.org/10.22059/IJMS.2021.320018.674466>
- Saksonova, S., & Kuzmina-Merlino, I. (2019). Cryptocurrency as an Investment Instrument in a Modern Financial Market. *Vestnik Sankt-Peterburgskogo Universiteta. Ekonomika*, 35(2). <https://doi.org/10.21638/spbu05.2019.205>
- Schmitz, T., & Hoffmann, I. (2020). Re-Evaluating Cryptocurrencies' Contribution to Portfolio Diversification – A Portfolio Analysis With Special Focus on German Investors. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3625458>
- Sinha, N., & Yang, Y. (2021). Strategic diversification for Asynchronous asset trading: Insights from generalized

- coherence analysis of cryptocurrency price movements. *Ledger*, 6. <https://doi.org/10.5195/LEDGER.2021.227>
- Su, C. W., Qin, M., Tao, R., & Umar, M. (2020). Financial implications of fourth industrial revolution: Can bitcoin improve prospects of energy investment? *Technological Forecasting and Social Change*, 158. <https://doi.org/10.1016/j.techfore.2020.120178>
- Wang, L. (2023). Portfolio Construction Based on the Modern Portfolio Theory Including Gold, Crude Oil and Cryptocurrency. *BCP Business & Management*, 38. <https://doi.org/10.54691/bcpbm.v38i.4296>
- Xie, Y., Kang, S. B., & Zhao, J. (2021). Are Stablecoins Safe Havens for Traditional Cryptocurrencies? An Empirical Study during the COVID-19 Pandemic. *Applied Finance Letters*, 10. <https://doi.org/10.24135/afl.v10i.342>
- Youssef, M., Naoua, B. Ben, Abdelaziz, F. Ben, & Chibane, M. (2023). Portfolio selection: should investors include crypto-assets? A multiobjective approach. *International Transactions in Operational Research*, 30(5). <https://doi.org/10.1111/itor.13203>
- Zhang, S., & Gregoriou, A. (2020). Cryptocurrencies in portfolios: return-liquidity trade-off around China forbidding initial coin offerings. *Applied Economics Letters*. <https://doi.org/10.1080/13504851.2020.1796908>